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Art VIII.—*Jurassic Arkose in Southern Victoria.*

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Abstract.

The Jurassic rocks of Victoria consist chiefly of arkoses and mudstones, with minor amounts of grit, conglomerate, and black coal, and have been derived from a terrane consisting of Palaeozoic sediments and igneous rocks (granites, granodiorites, dacites, and associated tuffs). The arkoses consist essentially of notably angular grains of quartz, oligoclase, orthoclase, biotite, and fragments of andesitic tuff, cemented together by chlorite, epidote, zoisite, and secondary felspar. Oligoclase is the dominant felspar. Calcite sometimes takes the place of the more usual cementing minerals. It often gives rise to epigenetic calcareous concretions in which it commonly replaces grains of oligoclase felspar, but not the orthoclase.

The arkoses were derived chiefly from the igneous rocks, whereas the mudstones were derived chiefly from the Palaeozoic sediments. The Jurassic mudstones differ from the Palaeozoic mudstones, however, in that they contain considerable amounts of lime and soda, and the iron in them is chiefly in the ferrous state. The iron appears to occur mostly as more or less colloidal size particles of a chlorite-like mineral.

Chloritic cement in the arkoses appears to have been deposited from the connate waters of the mudstones which migrated into the arkoses during the compaction of the sediments; and the CO_2 of the calcite cement is thought to have been set free during the decomposition of the plant remains that occur throughout the sediments.

The felspars in the arkoses are surprisingly fresh, and persist in a fresh condition, even in the soils derived from the Jurassic sediments. Their state of preservation does not seem to be related to the climatic conditions prevailing at the time of their deposition, because the Jurassic climate appears to have been moist and more or less temperate. The more angular felspar grains are much less decomposed than the sub-angular grains, suggesting that the freshness of the felspar is due to the fracture of coarser grains of felspar just prior to burying, rather than to the mode of weathering of the parent rocks. The subsequent preservation of the felspars was due to the sealing of the arkoses by the interbedded mudstones, while their preservation in the soils is probably due to the immaturity of the soils.

Contents.

Introduction.

The Jurassic sediments of Victoria are of fresh-water origin, and consist essentially of interbedded mudstones and felspathic sandstones, or arkoses, which commonly show current bedding, together with minor amounts of felspathic grit, conglomerate, and bituminous coal seams.

As shown on the Geological Map of Victoria, they occur in three main areas, one centering about Merino, in Western Victoria, and extending westwards to the Glenelg River, a second forming the mountains of the Otway Ranges, with a north-easterly extension in the Barrabool Hills, near Geelong, and a third forming the South Gippsland Highlands. The details of these, and other minor outcrops of the Jurassic rocks, in position intermediate between the main areas, have been published by Selwyn and Ulrich (1866), by Murray (1887), by Hunter and Ower (1914), and by Skeats (1935). The most westerly record of the Jurassic rocks is from a bore 4,504 feet deep at Robe in South Australia, in which Jurassic mudstones and thin coal seams were encountered below a depth of 1,450 feet (Ward, 1926). Their most easterly recorded occurrence is at a depth of 3,158 feet, in Bore No. 1 at Goon Nure, south of Bairnsdale (Ann. Rept. Dept. Mines, Vic., 1938, pp. 22, 40).

The estuarine or lacustrine origin of the sediments has long been recognized, but it is impossible to decide whether they were laid down in a single great estuary or lake, or in a series of large lakes, because of the extensive Tertiary earth-movements which have affected them. In the Otway Ranges the Jurassic sediments have been subjected to faulting, and possibly to warping (Hills, 1940, p. 268; Coulson, 1939), while in the South Gippsland Hills they have undergone block-faulting (Hills, 1940, p. 269) and warping (Edwards, 1942A). The uniform nature of the arkoses, and particularly the distribution throughout them of fragments of a distinctive andesite or andesite-tuff, suggest that a single basin of deposition was involved, and that the isolated nature of the present outcrops arises from the subsequent earth-movements.

The thickness of the Jurassic sediments is not known, but was estimated at 5,000 feet by Selwyn (1868, p. 19). Bores have penetrated to 3,032 feet at Coalville in South Gippsland, and to 2,804 feet at Yaugher in the Otways, without passing out of the Jurassic, and on this account Hunter and Ower (1914) also estimate the thickness of the Jurassic sediments as about 5,000 feet, making allowances for about 1,000 feet of erosion, and a possible downward extension of another 1,000 feet below the bottom of the bores.

A study of the boring records suggests that the arkose forms about 40 per cent. of the total sediments in the exposed areas. This figure has only a qualitative value, because many more bores have been put down in areas known to contain workable seams of coal than in the wider areas where the absence of such seams has been established. Moreover, the thickness of individual beds of arkose and mudstone, as recorded in the bores, is often such that a bore needs to be in excess of 1,000 feet deep before it can be accepted as a reasonable sample of the proportions of the two lithological types present. The recorded range of uninterrupted thicknesses of arkose is from less than an inch up to 433 feet, and the majority of bores record one or more uninterrupted thicknesses of 100 feet, while many show an uninterrupted thickness of 200 feet. Similarly the known range of uninterrupted thicknesses of mudstone is from less than an inch up to 461 feet, but the latter figure is unusual, and uninterrupted thicknesses in excess of 100 feet are recorded in only a small proportion of the bores, while thicknesses in excess of 200 feet have been recorded only occasionally. Another difference between the arkose and mudstone beds is that successive beds of arkose may show a tremendous variation in thickness, whereas successive beds of mudstone tend to less extreme variation. This is presumably because the arkose beds are much more lenticular than the associated mudstone beds. This lenticularity, and the irregular minor folding which is often found in the Jurassic sediments, probably arise from differential compaction during lithification. (Edwards, 1942B).

The relative proportion of arkose to mudstone varies considerably in different localities, though it remains relatively constant for a restricted area. This is shown both by field studies and by the bore records. A study of the bore records, using only those in excess of 1,000 feet depth, where such exist, and averaging the proportion of mudstone and arkose obtained where more than one bore was available for a single parish, yielded some qualitative data concerning the distribution of the two rock types. The figures obtained are, however, of unequal value, because of the few bores that have been put down in the Otway and Merino areas, and because many of the bores, particularly in the Merino area, are only shallow. They indicate, however, that the arkoses are most abundant in the southern parts of the South Gippsland Highlands and of the Otway Ranges, constituting from 60 to 70 per cent. of the thicknesses of Jurassic bored in those parishes which are probably near the southern margin of the Jurassic basin. Northwards from this margin there is a falling-off in the proportion of arkose to as little as 25 per cent.

In the Merino area, mudstone is the dominant rock (Dunn, 1912), and the evidence of all of the bores available, despite their relative shallowness, only two or three exceeding 700 feet, is that the arkose forms less than 40 per cent. of the thickness of Jurassic bores, and in most parishes less than 20 per cent., falling as low as 4 per cent. in the deepest bore (756 feet), in Muntham.

The mudstones weather much more rapidly than the arkoses (Hunter and Ower, 1914, plate 9), and where the country consists of thick formations of these two rocks interleaved with one another, the arkose formations outcrop as hills showing dip slopes and escarpments (Ferguson, 1908).

Arkoses.

Mineralogy.

The felspathic nature of the Jurassic sandstones, here termed arkoses, was first recognized by Selwyn (1853). The term arkose is used in the sense of Twenhofel (1932, p. 229), viz., "Arkose is a sedimentary rock composed of material derived from the disintegration of acid igneous rocks of granular texture." Brief petrographic descriptions of these rocks, from restricted localities, have been published by Richards (1910), Mahony (1922), Nicholls (1936), and Edwards (1942).

The present study is based on a collection of about 300 thin sections, largely drawn from areas in South Gippsland, but embracing the whole extent of the Jurassic outcrops. The greater proportion of this collection belongs to the Geological Survey of Victoria, the remainder being the property of the Geology Department of the Melbourne University. A noteworthy feature of the collection is that it includes sections of each successive change of lithology in four deep bores put down in South Gippsland. These are Bore No. 1 at Coalville (3,032 feet), the deepest bore in the Jurassic, Bore No. 1 at Powlett River (2,267 feet), Bore No. 1 at Berry's Creek, parish of Mardan (1,050 feet), and Bore No. 4 at Boolarra (900 feet).

The fresh arkose is characteristically greenish-grey in colour and is medium to fine-grained. The greater proportion of the grains are generally between 0·25 mm. and 0·50 mm. in diameter, and few exceed this size, though there may be a considerable number between 0·15 mm. and 0·25 mm. diameter, as is shown by Table 2. The fresh rock breaks across the grains, showing a dull matte-like surface, faintly speckled by the light-coloured felspar grains. The green colour arises from an abundance of chloritic cement. On weathering, the rock first becomes friable, and then, as the chlorite alters to limonite, the colour changes to brown. In thin section the grains are notably angular, particularly the quartz grains. Quartz, felspars, biotite, chlorite, and fragments of andesite are the essential components. The quartz and felspars are the more important constituents. Micrometric analyses show that the quartz forms from 10 to 15 per cent. by volume and the felspars 25 to 35 per cent., the higher figures in each instance coinciding with closer packing of the grains. Some of the quartz grains carry rows of dust-like inclusions, and very occasionally they are embayed after the manner of phenocrysts in acid lava-flows.

The felspars consist of oligoclase and orthoclase with minor amounts of perthite and microcline. The oligoclase is generally more abundant than the orthoclase and is commonly clear and limpid, whereas the orthoclase is generally cloudy. Very occasionally the felspar (generally orthoclase) is graphically intergrown with quartz.

Biotite is present as scattered flakes, often twisted or broken, and showing partial alteration to chlorite. Some of it is bleached, and most of the small amount of white mica present appears to be bleached biotite. Hornblende, pleochroic from green to brownish-yellow, and more or less altered to chlorite, is occasionally present, particularly in calcareous arkoses, as though the carbonate has had a protective effect, in the manner recorded by Bramlette (1942). Even in the calcareous rocks, however, it is generally much less abundant than biotite, except at Pebble Point, on the Otway coast, where it is the dominant ferromagnesian. Pyroxenes have been found only as very occasional grains.

Associated with these individual minerals, and constituting a distinct proportion of the rock, are sub-angular to rounded grains of an igneous rock. Some of these are glassy, others are micro-porphyritic, but all are of a uniform type. They consist of a fine-grained to glassy groundmass studded with microlites of a plagioclase showing almost straight extinction. In many grains the microlites show flow alignment. In others distinct micro-phenocrysts of andesine are present; and in some there are the chloritized remains of ferromagnesian minerals, so that the fragments are presumably derived from a fine-grained andesite, or an andesite tuff.

A calcareous arkose from Pebble Point contains fragments of sandstone, quartzite, mica-schist, chlorite schist, quartz schist, and what appear to be fragments of diabase tuff, in addition to the andesite fragments. Locally these rock fragments outnumber the normal mineral grains.

Cementing Minerals.

The chlorite, to which the rock owes its colour occurs as irregularly-shaped patches cementing the grains together. It is apple-green in colour, and under crossed nicols appears almost isotropic or cryptocrystalline. Associated with it are irregular or idiomorphic patches of zoisite and yellow epidote. All three appear to be authigenic minerals, formed probably by the action of connate waters, during the process of lithification. Accompanying the chlorite is a little sericite, and clay material sometimes fills the interstices between grains. Staining with malachite green indicates that the clay is chiefly kaolinite.

In many sections the margins of the grains and the chlorite areas are outlined by a narrow rim of a colourless, anisotropic material. This mineral has a refractive index distinctly lower than the chlorite, and slightly lower than that of the felspars. Its birefringence is similar to that of the felspars, into which it often appears to merge. Occasionally it forms minute spherulitic growths, and in one section it was observed filling the cells of a fragment of wood. The closeness of its refractive index to that of the felspars suggests that it is authigenic albite, but it may be a zeolitic substance.

Calcite is present in small amounts in a number of thin sections as a cementing mineral; and occasionally it completely replaces the chlorite, when it may form as much as 40 per cent. of the rock. Where the calcite is abundant, there is abundant evidence that it has more or less completely replaced grains of oligoclase, although it does not seem to attack the orthoclase.

Heavy Minerals.

Samples of arkose from ten widely-spaced localities were examined for their heavy mineral contents, with the results shown in Table 1. Bromoform, of specific gravity 2·889, was used in the separations. As indicated by the index numbers, the heavy minerals amount to as much as 1 per cent. of the sample in only three instances. Of these, the sample from Ceres, near Geelong, and that from Griffith's Point, near San Remo, contain much material derived from the nearby Palaeozoic granites and their contact aureoles. The arkoses from localities distant from areas of granite or Palaeozoic sediments have much lower index numbers. The minerals in each assemblage are characteristically those of granitic rocks and contact metamorphosed sediments, and are closely comparable with those found in the sand fractions of soils formed from the Jurassic rocks (Nicholls, 1936). Biotite occurs throughout the assemblages as fresh or partially altered flakes, and there is a distinct relationship between the amount of biotite and the amount of apatite present in a particular assemblage. Presumably the apatite is released from the biotite during the crushing of the specimen, since similar apatite crystals

TABLE 1.—TABLE OF HEAVY MINERALS FROM SOME VICTORIAN JURASSIC ARKOSES.

District.	Locality.	Rock.	Index Number.	Actinolite.	Apatite—clear.	Apatite—dusky.	Biotite.	Cassiterite.	Chlorite.	Cyanite.	Epidote.	Garnet—colourless.	Garnet—pink.	Garnet—brown.	Hematite.	Hornblende.	Ilmenite.	Leucoxene.	Limonite.	Magnetite.	Pyrite.	Rutile—red.	Rutile—yellow.	Sphene.	Topaz.	Tourmaline.	Zircon—crystals.	Zircon—waterworn grains.	Zoisite.	White Mica.
Merino ..	4 miles north of Casterton	Brown sandy mudstone	0·1	V	a	o	a	..	o	V	o	r	r	r	..	V	r	r	C	o	r	r	r	o	V	C	o	..	r	r
Otways ..	Pebble Point, Princetown	Grayish - green calcareous	0·6	V	..	..	r	V	r	..	o	r	o	V	o	A	C	o	V	o	C	V	..	o	..	V	o	..	o	V
	Point Hayley, Apollo Bay	Green ..	1·0	..	r	..	o	..	C	..	C	r	r	r	o	..	o	r	V	o	..	..	..	o	V	r	r	r	r	r
	Carisbrook Cr., Great Ocean Rd.	Grayish-green	0·6	..	o	V	C	..	o	..	o	r	o	r	V	..	o	r	o	..	V	r	r	o	V	r	r	V	V	r
Barrabool Hills	Ceres, near Geelong	Green ..	1·3	..	o	V	o	V	o	..	r	r	r	..	o	..	o	r	r	o	V	o	..	r	V	o	C	o	o	r
South Gippsland	Griffiths Point, San Remo Pen.	Grayish-green	1·0	V	o	V	o	..	A	..	r	r	V	..	r	..	o	r	r	..	V	r	V	r	V	r	o	..	V	..
	Mirboo East ..	Brown ..	0·2	..	V	..	o	V	r	..	C	..	..	r	..	..	o	..	o	V	..	..	..	r	..	o	o	r	V	..
	Middle Creek ..	Grayish - green mottled	0·08	..	o	r	o	..	a	V	o	r	V	V	..	..	r	r	r	..	..	..	..	..	..	r	o	V	r	r
	Stony Creek ..	Brown ..	0·08	..	o	V	o	V	o	V	..	r	r	r	..	V	..	r	A	..	..	..	..	..	..	o	V	..	..	r
	Brookleigh, Tara Valley	Green ..	0·3	..	o	r	C	V	C	..	o	r	r	r	o	V	o	r	..	..	V	..	..	r	..	r	o	r	V	V

Key.—A—very abundant; a—abundant; c—common; o—occasional; r—rare; V—very rare.

occur as inclusions in the biotite Some of the apatite crystals contain inclusions of a fibrous pleochroic material. Comparable inclusions are found in apatites in the Palaeozoic dacites at Dromana (Baker, 1938, p. 265) and at Marysville.

The preponderance of well-shaped zircon, tourmaline and rutile crystals over water-worn grains suggests that the bulk of these minerals has been derived direct from igneous rocks, but the occasional water-worn grains may have come from older sediments. The ilmenite has a fresh appearance, and shows only partial alteration to leucoxene.

The epidote and zoisite, as might be expected from their mode of occurrence in the thin sections, show no signs of water-wear. The garnets, of which there are three varieties, brown, pink, and colourless, occasionally show signs of water-wear. Some of the garnet grains are surprisingly large, despite the fact that they were separated from crushed rock. Anatase was met with as only very occasional grains in the Casterton sample, although Nicholls (1936) has recorded it from the sand fractions of soils from all three of the main Jurassic areas.

MUD PELLETS.

A number of the sections contain small rounded pellets of mudstone, which range in size up to a centimetre in diameter. Occasionally these pellets are so crowded together that the arkose appears as a cement filling the interstices.

WOOD FRAGMENTS.

Fragments of coalified wood are present in a number of the sections, including some from the deep bores. Not infrequently these fragments are sufficiently well preserved to show the patterns of the cell structure of the wood.

SIZING ANALYSES AND PARTICLE SHAPE.

Five samples of arkose were used for sizing studies. Of these, four were selected on account of their abundant carbonate cement, which made it possible to break down the rock by treatment with dilute acid, and so preserve the shapes and sizes of the grains. The fifth sample was a friable rock, easily broken down in water with a minimum of grinding. The samples were taken from three widely separated localities, and at two of the localities two samples were taken, a little distance apart in the same bed. The results obtained by screening these disintegrated rocks through sieves are set out in Table 2. They show that the rocks are medium to fine-grained, and that the degree of sorting is uniform within a given bed, but varies greatly from bed to bed, some rocks consisting of well-sorted grains, others of poorly-sorted grains.

TABLE 2.—SIZING ANALYSES OF JURASSIC ARKOSES.

Fractions.	+0·5 mm.	+0·25 mm.	+0·15 mm.	−0·15 mm.	Clay.
Pebble Point, Princetown, residue of calcareous arkose, 40 per cent. carbonate	0·4	81·4	9·6	3·1	5·5
Bourne Creek, Kilcunda, friable arkose ..	2·3	66·0	17·2	10·8	3·7
Bourne Creek, Kilcunda, residue of calcareous concretion, 25 per cent. carbonate	..	59·6	23·8	15·8	0·8
Tarra Valley, South Gippsland, calcareous concretion, 45 per cent. carbonate	..	36·8	30·6	24·7	7·9
Tarra Valley, South Gippsland, residue of calcareous concretion, 49·3 per cent. carbonate	..	38·5	31·2	25·2	5·1

Mounts of these various sized fractions revealed that in every instance the mineral grains were predominantly angular to subangular. Rounded grains were rare. The quartz grains were chiefly angular, with occasional subangular grains. The felspars tended to be tabular cleavage fragments, and showed rather more rounding, angular and subangular grains being present in about equal proportions. The subangular grains of felspar were generally cloudy, while the angular grains were almost always clear. A number of grains both of quartz and felspar were wedge-shaped splinters, with fine points, while others had delicate points or protrusions on their corners, so that, while they may have been fractured during transport, they cannot have undergone a great deal of abrasion.

The ferromagnesian and other heavy minerals were concentrated in the −0·15 mm. fraction. The abundant hornblende of the Pebble Point rock, the hornblende and biotite of the Tarra Valley rocks, and the biotite of the Kilcunda rocks, were all concentrated in this fraction. This, no doubt, is a result of sorting during transport, the greater specific gravity of these ferromagnesian minerals causing smaller grains of them to be associated with coarser grains of quartz and felspar. The occurrence of the heavy minerals in this fraction is due, no doubt, to their original occurrence as small crystals.

POROSITY.

Measurements of absorption capacity range from 2 per cent. by weight for fresh rocks, to 10 per cent. for weathered rocks. Low absorptive capacity is associated with high FeO content, while high absorptive capacity is associated with low or negligible FeO content, so that the increase in porosity with weathering arises from a volume shrinkage of the cement as the chlorite changes to limonite.

Chemical Analyses.

Comparison of the analyses of typical arkoses (Table No. 3) with available analyses of Palaeozoic sandstones from Victoria emphasizes the unusual composition of the arkoses. Their richness in alkalies and alumina, and their low silica contents, reflect their richness in felspars, while the dominance of soda over potash, and the abundance of lime, mark the preponderance of oligoclase over orthoclase. Variations in the individual analyses show that the total volume of felspar in the arkoses varies considerably from one locality to another, and that the relative proportion of orthoclase to oligoclase is equally variable, except that oligoclase is always the more abundant of the two. The plentiful chlorite in the arkoses is responsible for the unusually high FeO and MgO contents. In those analyses in which Fe_2O_3 dominates FeO, the samples were taken from weathered, brown rock, in which the chlorite is largely altered to limonite.

Table 3.—Analyses of Jurassic Arkoses.

—	1.	2.	3.	4.	5.	6.	7.	8.	9.
SiO_2	65·50	64·13	64·00	63·60	62·18	61·92	61·04	57·90	57·57
Al_2O_3	15·49	18·59	15·88	16·38	17·13	15·75	16·06	18·76	17·96
Fe_2O_3	0·36	1·99	1·90	0·97	0·87	3·12	2·57		
FeO	4·24	1·78	3·86	3·81	4·05	2·53	4·61	}4·20	4·27
MgO	1·92	1·24	1·81	1·92	2·60	2·47	2·55	1·31	1·51
CaO	3·50	1·34	2·02	2·15	2·19	2·13	1·92	3·40	1·38
Na_2O	2·60	4·36	3·42	4·19	2·15	2·76	2·00	2·88	2·64
K_2O	1·96	1·98	1·86	1·89	1·57	1·89	1·00	0·98	1·73
H_2O+ ..	1·89	3·43	3·84	3·02	0·96	4·05	4·13	3·65	5·37
H_2O- ..	0·54	1·38	1·04	1·18	3·31	1·78	1·90	4·35	6·57
CO_2	1·65	tr.	nil	tr.	1·32	..	..	1·77	0·50
TiO_2	0·60	..	..	0·69	..	0·81	0·87	0·81	0·72
P_2O_5	0·20	..	..	0·12	..	..	0·35	..	..
MnO	0·06	tr.	tr.	0·09	..	..	0·25	..	..
	100·51	100·22	99·63	100·01	98·33	99·21	99·25	100·21	100·22
Na_2O/K_2O ..	1·33	2·20	1·84	2·22	1·37	1·46	2·00	2·94	1·53

1. Arkose, cliff opposite Brookleigh, below the weir, Tarra Valley, near Yarram, South Gippsland; *Analyst*: A. B. Edwards.
2. Arkose, from McCann's Quarry, Ceres, Barrabool Hills; *Analyst*: H. C. Richards, *Proc. Roy. Soc. Vic.*, n.s., xxii, p. 194, 1909.
3. Arkose, from Apollo Bay, Otway Ranges; *Analyst*: H. C. Richards, *Ibid.*
4. Arkose, from Griffith's Point, San Remo, South Gippsland; *Analyst*: A. B. Edwards.
5. Arkose, from Apollo Bay, Otway Ranges; *Analyst*: P. G. W. Bayley, Rept. on Geol. Sheet A.47. *Spec. Rept. Dept. Mines*, 1901.
6. Arkose, from Craigleith Quarry, Pettavel Road, Barrabool Hills; *Analyst*: P. W. G. Bayley.
7. Arkose, near Coal Creek, Korumburra, South Gippsland; *Analyst*: P. G. W. Bayley.
8. Arkose, from No. 5 bore, State Coal Mine, Wonthaggi, South Gippsland; *Analyst*: F. F. Field.
9. Arkose, from dump in the Dudley Area, State Coal Mine, Wonthaggi, South Gippsland; *Analyst*: F. F. Field.

Another feature revealed by the comparison is the distinctly uniform SiO_2 and Al_2O_3 content of the arkoses as compared with the considerable range shown by these constituents in the more normal sandstones.

In Table No. 4 are shown the analyses of several arkoses in which the chloritic cement of the normal arkose has been more or less completely replaced by calcite, the culmination of this replacement being calcareous concretions (Table No. 4, Analysis No. 4), in which the carbonate content of the arkose rises as high as 50 per cent. of the whole. In these rocks the proportions of FeO and MgO remain unchanged, despite the absence of chlorite. In weathered specimens the ferrous carbonate has been converted to limonite. The unusually high MgO content of Analysis No. 3 in Table No. 4 suggests that some magnesium carbonate was introduced into the rock along with the calcium carbonate. Similarly the high MnO contents of the specimens showing most carbonate (Analyses Nos. 3 and 4 of Table No. 4) indicate that some manganese carbonate accompanied the calcium carbonate.

TABLE 4.—ANALYSES OF CALCAREOUS ARKOSES.

—	1.	2.	3.	4.
SiO_2	55·15	52·90	44·67	41·58
Al_2O_3	15·23	16·49	13·57	10·93
Fe_2O_3	4·49	0·78	4·87	2·40
FeO	0·98	4·86	2·76	1·89
MgO	2·79	2·92	3·82	1·30
CaO	5·43	7·14	9·97	21·06
Na_2O	1·16	2·58	1·18	1·86
K_2O	1·65	1·73	1·53	1·83
H_2O+	..	2·93	..	0·71
H_2O-	1·90	1·72	1·92	1·39
Ignition Loss	11·00	..	15·16	..
CO_2	..	4·65	..	14·93
TiO_2	0·59	1·10	0·52	..
P_2O_5	tr.	0·25	tr.	..
MnO	0·22	tr.	0·62	1·60
Cl	..	tr.	..	..
SO_3	nil	nil	nil	..
	100·59	100·05	100·59	101·48
Na_2O/K_2O	0·70	1·49	0·77	1·01

1. Calcareous arkose, allotment 76, parish of Longwarry, near Lang Lang River, South Gippsland; *Analyst*: F. F. FIELD, *Rec. Geol. Surv. Vic.*, 4, Pt. 4, 451.
2. Calcareous arkose, old shaft of Coal Creek Proprietary Mine, Korumburra, South Gippsland: *Analyst*: P. G. W. BAYLEY.
3. Calcareous arkose, allotment 74, parish of Longwarry; *Analyst*: F. F. FIELD, *Rec. Geol. Surv. Vic.*, 4, Pt. 4, 451.
4. Calcareous concretion in arkose (some manganese carbonate), Apollo Bay, Otway Ranges. *Analyst*: P. G. W. BAYLEY, *Spec. Rept. Dept. Mines, Vic.*, 1901 (Report on Geol. Sht. No. A. 47).

(Host rock, Analysis No. 5, Table 1.)

In three of these analyses (Nos. 1, 3, and 4, of Table No. 4) the Na_2O content is considerably lower than in any of the normal arkose analyses, being equalled or surpassed by the K_2O content. This confirms the evidence of the thin sections that the oligoclase in these rocks tends to be replaced by the calcite, while the orthoclase is not affected. Such replacement is not invariable, however, since in the fourth analysis (Analysis No. 2 of Table No. 4) the alkalies appear normal.

This variable behaviour of the carbonate on the felspars is further demonstrated by alkali determinations on the sand fractions of three of the rocks used in the sizing analyses (Table 2), namely, the residue of a calcareous concretion from near Brookleigh Farm, in the Tarra Valley, from which 49·3 per cent. of carbonate material had been leached with dilute hydrochloric acid; the residue of a calcareous concretion from near the mouth of Bourne Creek, at Kilcunda, from which 25 per cent. of carbonate had been leached; and the untreated fractions of a friable arkose from Bourne Creek, at Kilcunda. The alkali contents of the various fractions are shown in Table No. 5.

Table 5.—Alkali Contents of Sized Fractions of Arkoses.

Fraction.	K_2O.	Na_2O.	Na_2O/K_2O.
1. *Residue of Tarra Valley Concretion.*			
+0·25 mm.	4·21	2·03	0·48
+0·15 mm.	4·93	2·02	0·41
−0·15 mm.	4·62	2·55	0·55
2. *Residue of Kilcunda Concretion.*			
+0·25 mm.	2·48	3·50	1·41
+0·15 mm.	2·02	3·20	1·57
−0·15 mm.	1·77	2·50	1·33
3. *Friable Arkose from Kilcunda.*			
+0·25 mm.	2·19	3·16	1·44
+0·15 mm.	1·76	2·71	1·54
−0·15 mm.	1·39	2·01	1·44

The figures show that in the Tarra Valley rock a large proportion of the oligoclase has been replaced by calcite, while in the Bourne Creek concretion, little or no replacement of oligoclase has taken place. This is confirmed by the appearance of the felspars in thin sections of the two concretions.

Another feature of these partial analyses is that the total amount of felspar in the two Bourne Creek specimens diminishes as the grain size of the fraction decreases. This feature is not shown by the Tarra Valley specimen, but is probably true of the sediments as a whole, since thin sections show that the proportion of felspars in the sandy mudstones is always much less than the proportion of felspars in the arkoses. The figures indicate, however, that there is no significant or progressive variation in the ratio of potash to soda in the various sized fractions of a particular rock, so that apparently the comminution and destruction of both orthoclase and oligoclase proceeded at equal rates, and was not selective.

Concretions.

Calcareous Concretions.

Many of the arkose beds are characterized by calcareous concretions which are spherical, or less commonly, dumb-bell shaped. Their average diameter is between 3 and 6 inches, though some are larger. They are of epigenetic origin, since the bedding planes of the enclosing arkose pass through them without interruption. Occasionally these lines of stratification, as noted by Daintree (1862), are marked by films of coalified leaf remains. In the hand specimen the concretions appear identical with the enclosing arkose, but being harder, they project from weathered surfaces, especially cliff-faces and wave-cut platforms. They are generally structureless, though occasionally when weathered they break into concentric shells.

Thin sections show them to consist of the normal arkose minerals cemented together by coarse-grained crystals of calcite, the calcite sometimes invading and replacing the oligoclase. A typical concretion from arkose at Apollo Bay, in the Otway district, was found by V. R. Stirling (1901) to contain about 30 per cent. of calcite (Table No. 4, Analysis No. 4), while the enclosing arkose contained only 3 per cent. of calcite (Table No. 3, Analysis No. 5). That this is characteristic is shown by the fact that three concretions selected at random, two from the Tarra Valley, and one from Kilcunda, were found to contain 49·3 per cent., 43·5 per cent., and 25·0 per cent. of carbonate, respectively. In each instance the enclosing rock contained only a few per cent. of calcite cement.

The concretions do not occur in the shales or mudstones, and their restriction to the arkose is related to the higher porosity of these rocks. Presumably the concretions mark centres of slow crystallization of calcite from solutions filling the pore spaces of the arkose. The calcium carbonate in the adjoining rock was able to diffuse from all sides through the pore spaces to the widely spaced centres of crystallization, where it crystallized as a spherical meshwork of carbonate enclosing the mineral grains of the rock, at the same time converting the existing chlorite cement to carbonate. Insufficient carbonate was left in the surrounding rock to give it comparable hardness or bonding.

In other arkose beds calcite is present in abundance (Table No. 4, Analyses Nos. 1, 2, 3), but concretions have not formed. Either conditions did not permit diffusion to localized centres of crystallization, and crystallization occurred rapidly about many centres, or the supply of calcium carbonate was so great that the early-formed concretions continued to grow until the whole bed was cemented. The relatively small amount of carbonate in some of the beds, compared with the large amount in the concretions, suggests that the first explanation is the more probable. In places, however, there was an excess of carbonate available, and it formed veins of calcite, sometimes several feet thick.

Pyritic Concretions.

In the Apollo Bay district, Stirling (1901) noted small pyritic concretions in the arkoses, presumably of similar general origin to the calcareous ones. Such concretions do not appear to be numerous in other Jurassic areas. At Wyelangata, also in the Otway area, however, small nodules of pyrite and veins of pyrite and calcite, carrying as much as 2 dwt. of gold per ton, occur in the bedding planes of mudstone beds (Easton, 1935). Pyrite, associated with calcite, is also found in thin films in the joints of coal seams at Kilcunda.

Quartz Veins.

Stirling (1899) records the occurrence of thin quartz veins, carrying felspar, in the Jurassic near Mount Sabine.

Mudstones and Shales.

The mudstones and shales are generally blue or grey in colour, turning buff or brown on weathering. When rich in carbonaceous matter they are black. Like the arkoses, they are commonly current bedded. They range from sandy mudstone, containing numerous small angular fragments of quartz and a little felspar, in a fine-grained matrix of sericite and clay, to extremely fine-grained rocks in which little other than sericite can be made out with the microscope. The quartz grains, when present, are often wedge-shaped and sharp pointed. The proportion of felspars in the coarser mudstones and shales is always much less than that found in the arkoses, but both orthoclase and oligoclase are present. In the majority of mudstones examined there is an abundance of shreds and fibres of woody material, all the fibres lying parallel to one another and to the bedding planes, so they often reveal the presence of current bedding even in the finest grained sediments. This abundance of wood fibres indicates that broken-down plant remains were being supplied continually to the Jurassic basin of sedimentation.

The clay matrices of several samples were extracted, and tested by staining with malachite-green and saffranine-o, both before and after treatment with hydrochloric acid (Faust, 1940). This showed that in addition to kaolinite the clays contained a considerable proportion of a mineral or minerals subject to base exchange. A partial analysis of the composite fine clay remaining in suspension after twelve hours, from a typical blue mudstone from Cape Paterson, gave the results shown in Analysis No. 6, Table No. 6. Since as much as one-third of this material consisted of kaolinite, the mineral showing base exchange must be an iron-rich variety containing relatively little alumina.

It differs, however, from all the iron-rich clay minerals in that the bulk of its iron is in the ferrous state, whereas in the iron-rich clays the iron is in the ferric state. That this is general in the Jurassic mudstones is shown by the dominance of ferrous iron over ferric iron in their analyses (Table No. 6). This is in equally striking contrast to the state of the iron in the more normal Palaeozoic slates and mudstones in Victoria in which the iron is chiefly in the ferric state. According to Grim (1939), the common clay mineral of such rocks is illite. The clay-like mineral in the Jurassic mudstones, however, must be more akin to a chlorite in a very finely divided state.

When the analyses of the mudstones (Table No. 6) are compared with those of the arkoses (Table No. 3), considerable resemblances are noted, and certain differences. The SiO_2 content of the mudstones is much the same as that of the arkoses, and

TABLE 6.—ANALYSES OF JURASSIC SHALES.

—	1.	2.	3.	4.	5.	6.
SiO_2	61·36	60·70	59·72	57·83	57·40	53·57
Al_2O_3	18·18	18·32	19·26	18·49	20·44	18·05
Fe_2O_3	4·26	1·18	0·80	0·41	1·14	1·95
FeO	..	3·18	3·06	1·79	2·44	13·35
MgO	1·26	2·02	1·92	1·59	1·50	2·81
CaO	1·68	2·00	0·82	1·53	0·98	nil
Na_2O	1·94	1·25	1·44	1·52	1·41	1·16
K_2O	3·32	2·64	4·17	2·42	3·66	2·09
H_2O+	4·23	4·13	5·01	7·72	5·99	..
H_2O-	3·10	3·35	3·50	5·32	3·63	..
TiO_2	..	0·90	0·99	0·63	0·90	0·60
P_2O_5	..	tr.	tr.	nil	tr.	
Cl	..	tr.	nil	tr.	nil	..
SO_3	..	nil	tr.	tr.	nil	..
	99·33	99·67	100·69	99·25	99·49	..

1. Shale from the roof of the Outtrim Colliery, South Gippsland; *Analyst*: F. E. A. STONE, *Ann. Rept. Sec. Mines*, 1898, p. 28.
2. Shale from above coal seam, east adit near shore, Kilcunda; South Gippsland; *Analyst*: P. G. W. BAYLEY, *Ann. Rept. Sec. Mines*, 1906.
3. Shale from above seam in Coal Creek Mine, Korumburra, South Gippsland; *Analyst*: P. G. W. BAYLEY.
4. Shale forming the seatstone in coal mine, Kilcunda, South Gippsland; *Analyst*: P. G. W. BAYLEY, *Ann. Rept. Sec. Mines*, 1906.
5. Shale from under coal seam in Coal Creek Mine, Korumburra; *Analyst*: P. G. W. BAYLEY, South Gippsland.
6. Composite clay fraction remaining in suspension after 12 hours, from blue Jurassic mudstone, Cape Paterson; *Analyst*: A. B. EDWARDS.

shows much the same range of variation. The Al_2O_3 content of the mudstones is a little higher than that of the arkoses of corresponding SiO_2-content. Lime, magnesia and iron oxides are present in much the same amount, and alkalies are still abundant; but whereas Na_2O is the dominant alkali in the arkoses, K_2O is dominant in the mudstones. In this respect the Jurassic mudstones and shales approach more closely to their Palaeozoic equivalents, which are dominantly potassic (Howitt, 1923), than do the arkoses. The consanguineous relationship between the mudstones and the arkoses is shown, however, by their Na_2O and CaO contents, which are unusually high for such rocks, and arise from the abundance of plagioclase in their source material.

A minor but interesting difference between the arkoses and the mudstones, is the relative abundance of P_2O_5 in the arkose, in contrast with its relative absence from the mudstones. The P_2O_5 in the arkose occurs in small apatite crystals enclosed in biotite flakes, and with the increased comminution of the biotite flakes these apatite crystals were set free and then dissolved.

The mudstones, like the arkoses, have a relatively uniform composition, and hence a much more restricted range of composition than is shown by the normal Palaeozoic mudstones and slates.

Felspathic Grits.

Thin beds of felspathic grit occur at a number of places along the Otway and South Gippsland coasts, and in the Barrabool Hills. They are most prominently developed at San Remo, where they outcrop in the vicinity of Griffith's Point, and along the Western Port coast of the peninsula (Edwards, 1942B). Small pebbles of granite, arenaceous sandstone, shale, and slate are intermingled with the grit. The material is clearly derived from the nearby granite of Cape Woolamai, and the sediments of its contact aureole. Felspar has been separated from the quartz during deposition, so that quartz predominates in the grit. An alkali determination on a specimen practically free from mica and pebbles gave the values K_2O 1·99, Na_2O 1·39, as compared with K_2O 4·76, Na_2O 3·00, in the granite (Summers, 1914). The ratio of potash to soda in the grit is not significantly different from that in the granite, so that there has been no differential winnowing of orthoclase or oligoclase from the quartz during the formation of the grit, but merely of felspar from quartz. Where the grits are calcified, the calcite is found replacing the oligoclase in the grit, but not the orthoclase.

At Apollo Bay the grits occur as thin beds and lenses interstratified with arkose, as at San Remo, and again consist chiefly of granitic material with quartz grains preponderating. There are no outcrops of granite in the vicinity, but the character of the grits suggests that granite must occur somewhere nearby, either beneath the Jurassic sediments, or under the sea.

In the Barrabool Hills, similar grits are exposed at Buckley's Gorge, on the Barwon River (Coulson, 1930), where they are interbedded with arkoses, and with thin beds of conglomerate carrying granitic and other boulders.

The heavy minerals obtained from these grits are set out in Table No. 7. They are of a granitic nature. The zircons in both grits examined include both prismatic and water-worn forms, the water-worn zircons being the less numerous. The apatite crystals sometimes have coloured, pleochroic cores, like those found in Victorian granites (Baker, 1941). Some of those in the Apollo Bay grit contain inclusions of a fibrous pleochroic material. The ilmenites show partial alteration to leucoxene.

TABLE 7.—HEAVY MINERALS IN JURASSIC GRITS.

Mineral.	San Remo.	Apollo Bay.
Apatite	r	o
Biotite	r	a
Bleached Biotite	C	o
Chlorite	o	o
Epidote	..	r
Garnet	r	r
Hornblende	..	V
Ilmenite	o	o
Limonite	a	..
Magnetite	..	o
Rutile	V	r
Sphene	V	r
Tourmaline	r	o
Zircon	o	o
Zoisite	..	r

Key.—a—abundant; o—occasional; C—common; r—rare; V—very rare.

Conglomerates.

Two types of conglomerate occur in the Jurassic rocks; (1) those containing pebbles drawn from the Jurassic terrane, and (2) those in which the pebbles are all derived from earlier deposited Jurassic mudstones and arkoses. The greatest known development of the first type of conglomerate is exposed along the Tyer's River in South Gippsland, where it marks the boundary between the parishes of Tanjil East and Boola Boola (Murray, 1876; Whitelaw, 1899). Cliff sections along the eastern side of the Tyer's River show more than 100 feet of conglomerate resting unconformably on the Silurian, and dipping at from 5 to 12 degrees south. The conglomerate consists of well-rounded large and small pebbles of hard Silurian sandstone, quartzite, and quartz, in a sandy matrix, with a cement of iron oxide. Some indication of bedding can be seen in the conglomerate, with which are intercalated sandy and shaly patches, sometimes carrying plant remains. To the south the conglomerates pass beneath normal arkose and shale beds.

A similar conglomerate is exposed in the banks of Rintoul's Creek, to the east, but it is not so thick at this locality, and contains smaller pebbles of somewhat softer Silurian rocks.

Conglomerates with pebbles of pre-Jurassic rocks occur at a number of other localities, both in the Otways and in South Gippsland, but they nowhere else attain such a volume. Along the Otway coast they have been recorded as thin beds and lenses, associated with grits and arkoses, from Pebble Point (Wilkinson,

1864) and Castle Cove (Kitson, 1900). In the Barrabool Hills, they are exposed at Buckley's Gorge, on the Barwon River, near the local base of the Jurassic (Daintree, 1861; Wilkinson, 1864; Coulson, 1930). Marginal conglomerates, up to 3 feet thick, occur interbedded with grits and arkoses at Griffith's Point, near San Remo on the South Gippsland coast (Stirling, 1892; Ferguson, 1908; Edwards, 1942). Similar conglomerates occur in the Jumbunna district, where they form beds about 10 feet thick (Kitson, 1917).

Some of the Jumbunna pebbles are polished, and Kitson suggests they are derived from Permian (Permo-Carboniferous) glacial conglomerate beds.

At Chitt Creek, near Toora, Ferguson (1906) has described a lenticle of somewhat similar conglomerate at the junction of the Silurian with the overlying Jurassic. The pebbles consist of granite, resembling that of Wilson's Promontory, indurated sandstone and grit, chert, quartzite, felsite, and siliceous shale. Some of the pebbles were polished, striated and facetted, while others were not. Ferguson suggested that this conglomerate bed, which is about 3 feet thick, is of glacial origin, but Kitson (1917) is of the opinion that this and similar conglomerates in the Jurassic may be derived from resorted glacial beds of Permian age. Mahony (1930) classes this conglomerate and similar basal conglomerates underlying the Jurassic at Coleraine as of Permian (Permo-Carboniferous) age.

Isolated pebbles and boulders of foreign origin are sometimes found in the mudstones and arkoses, being more numerous in the coarser-grained sediments. Ferguson (1906) records the occurrence of two large boulders of granite near Kilcunda, while Hunter and Ower (1914) describe a pebble of granophyric granite found in the roof of No. 5 coal seam at Wonthaggi. Near Anderson's Inlet there are highly-polished pebbles of felsite, mica-schist, jasper, agate, carnelian, quartzite, quartz, sandstone, and silicified wood in the arkoses (Kitson, 1903). Felsite has been recorded from Waratah Bay (Stirling, 1894), but the other rocks are foreign to the district.

The second type of conglomerate, in which the pebbles all consist of Jurassic mudstone and sometimes arkose, and even coal, is of more frequent occurrence, but rarely exceeds a length of 20 feet, or a thickness of more than a foot. Kitson (1917) has described such conglomerates in the Jumbunna district, where he found pebbles and boulders of mudstone ranging in size from 2 inches by ½ inch up to 7 or 8 feet by 2 or 3 feet. In some rounded mudstone " boulders " over a foot in diameter he found well-preserved plant remains and casts of *Unio*. In other beds there were numerous rounded to sub-angular pellets of mudstone, many of them flattened and oval shaped. Some of these may have been "mud curls." Conglomerates of this type are exposed along the San Remo coastline (Edwards, 1942), and at Cape Paterson (Ferguson, 1908), along the Otway coast (Wilkinson, 1864; Kitson, 1900), and in the Barrabool Hills (Coulson, 1930). They are well developed in places in the roofs of the coal seams in the Wonthaggi State Coal Mine, where they form lenses 1 to 3 feet thick, extending over areas of an acre. They clearly arise from contemporaneous erosion of the Jurassic beds, and sometimes have themselves suffered erosion soon after deposition. Kitson (1917) describes such an occurrence in the Jumbunna district, where pebbles of coal in such a conglomerate have been partially eroded, and fresh arkose beds deposited on the eroded faces of the pebbles.

Coal Seams and Plant Remains.

Thin seams of black coal occur at a number of places in the various Jurassic areas, but workable seams are restricted to a belt about 50 miles long and 10 miles wide, running north-east from Kilcunda (Hunter and Ower, 1914). The individual seams are lenticular, and extend over only small areas. The best seams average between 2 and 3 feet thick, occasionally attaining thicknesses of as much as 9 feet, and they are generally much faulted. The coal is worked in the State Coal Mine at Wonthaggi (Platt, 1940), and in smaller mines at Kilcunda, Korumburra and Jumbunna. The coal at Korumburra and Jumbunna is of higher grade than that at Wonthaggi and Kilcunda, suggesting that there was a greater thickness of sedimentary cover in this part of South Gippsland.

Most workers have considered that the coal is of drift origin (Selwyn, 1853; Murray, 1895; Stirling, 1895; Kitson, 1917). The evidence cited in favour of such an origin is the absence of old soils beneath the coal seams; the occurrence of seams with both floor and roof consisting of arkose, or with a floor of arkose; the presence of current bedding in the rocks forming the roof and floor of the seams; the presence of quartz pebbles in the coal at Korumburra and Jumbunna, unaccompanied by any sandy material; the presence of fossil branches, roots, and tree trunks in the arkose beds, in positions in which they could not have grown. Hunter and Ower (1914), on the other hand, consider that the coal vegetation grew *in situ,* but offer little evidence in support of their belief.

The surface of the coal-forming peat was subject to contemporaneous erosion, since small washouts filled with arkose occur in the Kirrak and Shaft 18 areas of the State Coal Mine at Wonthaggi. One such washout in the Kirrak area failed to cut to the base of the coal seam, and is overlain by a 2-inch thick band of dirt (arkose) above which is about 12 inches of good coal. In this area of the mine the roof of the seam consists of arkose, sometimes showing current bedding and containing waterworn pebbles. Occasionally it gives place to runs of fine conglomerate.

The coal is bituminous, and is generally very finely banded, the individual bands or lenses of coal being as thin as 0·01 inch. Vitrain forms only a small proportion of these bands, the bulk of them consisting of dull coal. Occasionally, however, bands of vitrain occur as wide as 0·5 inches. Banding in coal is generally regarded as due to fluctuations in the water conditions of the swamp in which the coal vegetation grew (White, 1932), but there is a possibility that in these seams it might be due to deposition of drifted material. In a number of localities the arkoses occur as thin beds, often less than a centimetre thick, each bed separated from the next above by a thin layer of coalified leaf remains and wood fragments. Several hundred such beds may be exposed in a few feet in a single cutting. Deposition of the wood fragments without the intervention of the thin beds of arkose could well have given rise to a thin coal seam.

Plant Remains.

No doubt can be entertained of the drifted nature of fragmentary plant remains just described, nor of the small twigs and branches of coalified wood found along the bedding planes of the arkose beds at many localities. Further evidence of drift is provided by the countless fibres of woody matter found in the mudstones.

The plant remains occurring in the arkose beds are generally fragmentary and waterworn, but well preserved, and often delicate, leaf remains are found in the mudstones. The Jurassic flora has not been studied exhaustively, but sufficient work has been done to reveal its general nature (Seward, 1904; Chapman, 1908, 1909; Stirling, 1900). It resembles the flora of the estuarine phase of the Yorkshire Oolite. There is a tendency for one or two species to predominate at any given locality, but they do not appear to be restricted to any particular horizon in the Jurassic, nor to provide a basis for zoning the deposits.

The only other fossils recorded are an occasional *Unio* (Selwyn, 1866; Stirling, 1900; Kitson, 1917), a few fossil fish (Etheridge, 1902; Woodward, 1907; Chapman, 1908), and the claw of a carnivorous Dinosaur (Woodward, 1907).

The Source Rocks.

By definition, the composition of an arkose is a direct reflection of the composition of the rocks from which its constituents are derived, and where the arkose extends over a wide area, it may be expected to show local variations in accordance with the changing nature of its terrane.

Such relationship appears to hold for the Jurassic sediments in Victoria. The Jurassic terrane consisted predominantly of Palaeozoic sediments, chiefly of Ordovician and Silurian age, and of Palaeozoic granitic rocks, porphyritic extrusives, and tuffs, with much less extensive outcrops of Cambrian sediments and epidiorites, of Carboniferous sandstones and shales, and of Permian tillites and glacial sandstones; and it is possible to trace, in some degrees, the contribution which each made to the Jurassic basin of sedimentation.

The clearest evidence of the origin of the source material is provided by the pebbles in the marginal conglomerates and grits of the Jurassic, which are largely derived from nearby Palaeozoic igneous rocks and sediments, as for example at the Barrabool Hills, where the Jurassic conglomerate contains pebbles of the nearby Heathcotian epidiorite, and of granite and contact metamorphosed Palaeozoic sediments, or at Tyers River, where the boulders consist essentially of Silurian sediments. Further evidence is provided by the marked difference in mica content between the Palaeozoic sediments and the Jurassic sediments. In the Palaeozoic sediments, especially those of Silurian age, muscovite is the predominant mica (Langford, 1916; Dunn, 1921), whereas it is a relatively uncommon mineral in the Jurassic rocks. In the Jurassic rocks, biotite is the dominant mica, and the bulk of the small amount of white mica present appears, from its specific gravity, which exceeds 2·889, to be bleached biotite. This predominance of biotite in the Jurassic rocks can only be attributed to the fact that biotite is the dominant, and often the sole, mica in the Palaeozoic granitic and extrusive rocks in the vicinity of the Jurassic sediments. The biotite, both in the Jurassic rocks and in the Palaeozoic igneous rocks, is characterized by inclusions of apatite crystals. Moreover, the hornblende which sometimes accompanies, or more rarely takes the place of, the biotite, is closely comparable with the hornblende found in certain of the Palaeozoic granitic rocks.

A small proportion of the felspar in the Jurassic arkoses may have come from the Palaeozoic sediments, since the Silurian sandstones contain a small proportion of fresh oligoclase (Junner, 1913; Langford, 1916) and the Ordovician carries small amounts of weathered orthoclase and oligoclase (Dunn, 1921), but the bulk of it was probably derived from the Palaeozoic igneous rocks. The excess of oligoclase over orthoclase in the arkoses is difficult to explain in terms of present exposures. Most of the orthoclase, and a large part of the oligoclase must have been drawn from the granitic rocks, considerable areas of which are hidden by the waters of Bass Strait, and the basalt plains of Western Victoria. These comprise granites, adamellites, and granodiorites. The relative proportions of the three are unknown, but it is unlikely that the granodiorite is sufficiently preponderant to account for the whole of the oligoclase in the arkoses. Micrometric analyses of the granitic rocks (Baker, 1942) show that, taken as a whole, they are not likely to contain more than about 30 per cent. by volume of oligoclase to 25 per cent. of orthoclase, and the Na_2O/K_2O ratio for such of them as have been analysed ranges from 0·67 to 1·42, while for the arkoses it ranges from 1·33 to 2·94, the average for nine analyses being 1·88. Part of the Na_2O in the arkoses occurs, of course, in fragments of andesite or andesite-tuff and as authigenic albite, but even so their Na_2O content could scarcely be accounted for by the granitic rocks unless they consisted predominantly of granodiorite.

Some proportion of the felspar in the arkoses came from the extensively eroded dacites and rhyodacites of Dromana (Baker, 1938), and the Dandenong Ranges (Richards, 1909; Morris, 1914). In the majority of these rocks oligoclase phenocrysts greatly outnumber orthoclase phenocrysts, sometimes to their complete exclusion, as in the hypersthene-dacites of the Dandenong Ranges, in which oligoclase phenocrysts constitute about 25 per cent. by volume of the rock. Whether a sufficient volume of oligoclase could have been obtained from the original outcrop of these rocks, and whether it could have been spread so uniformly through the wide extent of Jurassic sediments from these centralized sources is open to considerable doubt. The difficulty can be overcome only by assuming, as do Hunter and Ower (1914, p. 195), that closely similar rocks occurred in the requisite volume in association with the granitic rocks that are known to exist beneath the waters of Bass Strait. Quartz-felspar-porphyry, or rhyodacite, closely resembling the Victorian rhyodacites, occurs in the south-eastern part of King Island, in the vicinity of the Bismuth Products mine.

Some proportion of the oligoclase may have been drawn from the same source as the fragments of andesite or andesite-tuff that are so characteristic of the Jurassic arkose beds. The source of these fragments cannot be established with assurance, but the available evidence suggests that they come from flows of andesite, or beds of andesite-tuff associated with the Upper Devonian dacites. It was suggested earlier (Edwards, 1942) that they represented tuff fragments falling into the Jurassic lake, but it was not realized then how uniformly the fragments are dispersed throughout the arkoses. Moreover, there is no evidence of contemporaneous igneous activity in this part of Australia. The Mesozoic igneous activity which gave rise to the great dolerite intrusions in Tasmania did not, apparently, lead to the formation of extrusive rocks. These intrusions did not develop until at, or near, the close of the Trias-Jura sedimentation in Tasmania, and, in view of the undifferentiated nature of the dolerite magma at the time of its intrusion (Edwards 1942c), it is most unlikely that it could have given rise to andesitic tuffs or lava flows.

The probability is, therefore, that the andesite fragments were derived from extrusive rocks or tuff beds associated with the Upper Devonian dacite suites, and it is significant in this connection that they can be matched with practically identical andesite fragments in a thick bed of tuff recently discovered along the eastern margin of the hypersthene-dacites of the Dandenong Ranges. This tuff bed, which is as yet undescribed, dips steeply towards the south-west, and apparently underlies the hypersthene-dacite. The steep dip indicates that a considerable volume of it has been eroded. Fragments of this andesite are abundant in the Lower Dacite flows at the northern end of the Dandenong Ranges, and fragments of somewhat comparable andesite are numerous in the rhyodacites of the Black Spur district (Edwards, 1932), so that there is some reason for thinking that rocks of this type may have been as widespread as the other Upper Devonian extrusive rocks with which they are associated.

The markedly greater potash content of the Jurassic mudstones and shales, compared with that of the arkoses, cannot be attributed to selective destruction of the oligoclase and concentration of orthoclase in the residue with increased comminution of the felspar grains, because the analyses of the sized fractions of the arkoses show that this did not happen (Table 5). It is rather a reflection of the contribution made by the Palaeozoic sediments to the Jurassic lake. The Ordovician and Silurian sediments, which make up the great bulk of these rocks, consist of sandstones, mudstones, shales and slates, with very occasional beds of limestone and conglomerate. The material from the sandstones, being largely quartz, served chiefly as a diluent to the felspars from the igneous rocks. Material from the mudstones, shales and slates must, however, have joined the more finely comminuted material from the igneous rocks, and since the fine-grained Palaeozoic sediments are dominantly potassic (Howitt, 1923), it follows that the marked increase in the potash content of the Jurassic mudstones relative to that of the arkoses is a reflection of the differential distribution of the sedimentary source material. Whereas the arkoses reflect chiefly the igneous aspect of the Jurassic terrane, the mudstones reflect chiefly its sedimentary aspect.

It is probable that the Permian tillites and glacial sandstones also contributed material to the Jurassic lake, but, since these rocks do not differ greatly in essential constituents from the other Palaeozoic source rocks, the extent of their contribution cannot be estimated. That they did contribute is suggested, however, by the nature of the garnets in the Jurassic rocks. The smaller, colourless and pink garnets in the arkoses probably came from the Lower Palaeozoic sediments, since these carry such garnets (Langford, 1916). Many of the colourless and pink garnets in the arkoses are distinctly larger, however, than those in the

Ordovician and Silurian sandstones, and these must have been derived from the Palaeozoic igneous rocks (Edwards, 1936; Baker, 1942), or from the Permian sediments (Scott, 1937), in which similar coarse garnets occur. The brown garnets of the arkoses have been matched only in the Permian sediments, and in the igneous erratics that accompany them, in the Bacchus Marsh district, where they have been noted in heavy mineral mounts prepared by Scott, though not recorded by him. The other possibility is that such garnets were derived from the rocks from which the erratics were drawn.

Origin of the Arkose.

Owing to the readiness with which felspars decompose when exposed in humid climates, an abundance of more or less fresh felspar in a sedimentary rock is commonly taken as an indication that the sediment was formed under arid or glacial conditions, such as would inhibit chemical weathering of the felspar during the breakdown of the parent rock and during transportation (Mackie, 1899). It is recognized that arkoses can be formed under the conditions of moist and temperate climates, but such arkoses have been thought to be of secondary importance only, and to be characterized by partially decomposed felspars (Barton, 1916).

This view of the relationship of felspars to climate has been challenged, however (Reed, 1928). The proportion of felspars in the arkoses deposited throughout the Cainozoic period in California has been found to remain unchanged, despite the gradual change of the climate of that region from a humid sub-tropical climate during the Eocene to a sub-boreal, semi-arid climate in the Pliocene, so that the long continued deposition of arkoses was independent of the climate (Reed, 1933). The preservation of the felspars in arkoses formed under humid climates is attributed to rapid deposition of the felspathic sediment, so that the felspars in it are " sealed " from further decomposition (Hatch, 1938).

The Jurassic Climate.

Sussmilch (1941) has suggested that the climate of Eastern Australia during the Jurassic period was not greatly different from the present climate. The evidence in Victoria is somewhat scanty. Absence of any stratigraphical break in the Jurassic implies the continued existence of an extensive fresh-water lake or estuary throughout the period of sedimentation, and hence a rainfall adequate to maintain such a water body. The abundant presence of plant remains, whether they grew in the hinterland, or in swamps in the lake, is further evidence of a moist climate; and the combination of ferns and coniferous trees that make up the flora suggests a moderate rather than an extreme temperature.

The possibility that glacial conditions existed during the early stages of the Jurassic sedimentation has been suggested by Ferguson (1906) to account for a supposedly Jurassic glacial conglomerate near Toora, in South Gippsland, but this view has been discounted on the grounds that this inextensive conglomerate, and some others elsewhere in the Jurassic, may be re-sorted Permian glacial deposits (Kitson, 1917). The presence of floe-ice has been envisaged as the transporting agent of the sporadic foreign pebbles found in the arkoses and sometimes in the mudstones (Kitson, 1917); but floating vegetation may have been responsible for their carriage. Moreover, the presence of *Ceratodus* and of large *Unios* in the sediments points to warm rather than cold conditions.

The abundant flora and coal seams of the Upper Triassic of Tasmania (Nye and Blake, 1938) suggest that the climatic conditions during this period were not greatly different from those of the Jurassic. Somewhat drier conditions may have prevailed, however, during the preceding stage of the Triassic, since local deposits of rock salt and epsomite are found in the Ross Sandstone series of Tasmania.

There is little, therefore, to suggest that the climate was sufficiently arid, or sufficiently cold, to greatly inhibit the decomposition of the felspars in the Jurassic terrane; and this finds support from the state of the felspars themselves, since a proportion of them are cloudy from partial decomposition, even in the freshest rocks.

The Conditions of Deposition.

The prominence of current bedding in the arkoses, and, to a somewhat less extent in the mudstones, leaves little doubt that they were "formed in shallow water under the influence of strong and constantly changing currents" (Selwyn, 1866, p. 18). The boring records show that the current bedding is characteristic throughout the explored thickness of the Jurassic. This feature led Murray (1884, p. 84) to suggest that some of the arkoses might be of wind-blown origin, but the angularity of the mineral grains disposes of this possibility.

The depth of water fluctuated since the sediments were subject to contemporaneous erosion. The top-set portions of current bedded arkoses were sometimes truncated, and previously formed beds, particularly of mudstone, were eroded, with the formation of conglomerates in which the pebbles consist chiefly of Jurassic mudstone. Occasionally, these "contemporaneous" conglomerates were eroded in their turn. Even the coal was subject to erosion, since some of these conglomerates contain pebbles of coal. If the interpretation of some of the mudstone pellets as "mud curls" is correct, the bed of the lake must have been exposed from time to time in some parts. The occurrence of washouts in the coal seams at Wonthaggi also points to this, as do occasional current ripple marks found in the State Coal Mine.

The preservation of the mud pellets and pebbles in the "contemporaneous" conglomerates suggests that they were rapidly reburied; otherwise such soft, recently-formed material would have been worn down to its component grains. The rapid alternation of extremely thin beds of arkose with films of plant remains also points to rapid deposition, and so does the well-preserved appearance of delicate fern fronds in some of the mudstones. Again, in many pieces of silicified wood, the grain is often beautifully preserved, suggesting that the wood was quite undecomposed when buried. This seems the more probable since in one specimen from Jumbunna the wood appeared to have undergone partial decay before silicification (Kitson, 1917).

Fresh Felspar.

The angular nature of the mineral grains, and the fact that even in the arkoses the individual grains are considerably smaller than those found in the Palaeozoic granitic rocks, shows that the mineral grains have been fractured during transport. Such fracturing probably accounts for the presence of the abundant grains of fresh felspar. Chemical weathering of a felspar crystal extends from the surface inwards, so that if a large crystal is fractured, some of the fragments that result may consist of fresh felspar. These fragments will then begin to weather at the surface in their turn. This seems to be what has happened in the Jurassic arkoses. As the examination of the sized fractions of the arkoses showed, in each fraction the angular, and presumably freshly broken, grains of felspar were clear and limpid, while the sub-angular grains, which had undergone more prolonged transport since being fractured, were generally cloudy from decomposition. It would appear, therefore, that angular fragments of fresh felspar can occur in a sediment quite independently of the climate under which the sediment was formed.

The angularity of the grains also indicates that the sediments suffered relatively little wear during transportation, or alternatively that transportation was not prolonged. The relatively fresh state of preservation of biotite, which is regarded as one of the chemically less stable minerals (Twenhofel, 1932, p. 226), is a further indication that the sands did not undergo prolonged transportation, though in view of recent work on the stability of minerals such evidence must be treated with caution (Russell, 1939, p. 44).

Such evidence as can be obtained points then to relatively rapid deposition in shallow waters subject to current action. This, combined with the interleaving of mudstone with arkose, resulting from fluctuating depth of water, would provide the necessary conditions for the formation of a "sealed deposit" in which fresh felspars might be preserved.

Diagenesis.

The carbonate cement of the calcareous arkoses was clearly introduced after the deposition of the sediments; and since the interstratification of the arkose beds with mudstone must have "sealed" them from surface waters, it seems likely that the carbonates were deposited from the connate waters in the sediments. Presumably the carbon dioxide was obtained from the plant remains during their decomposition or carbonization, while the lime was largely derived from comminuted plagioclase, since the carbonate readily attacked the oligoclase. The pyrite nodules and veins may have had a somewhat similar origin, since pyrite and calcite occur together in the joints of the coal. The sulphur of the pyrite may have been set free as hydrogen sulphide during the decomposition of plant remains, in which pyrite is unusually abundant.

The chlorite cement, with its associated zoisite, epidote and (?) albite, was also formed, no doubt, after the deposition of the sands, from substances in solution in the connate waters. The ferromagnesian minerals in the arkoses generally show partial alteration to chlorite, but they are not as abundant as the chlorite cement. The felspars, on the other hand, are often fresh and angular, so that they have not undergone much alteration or solution *in situ*, except where attacked by calcite. It seems, therefore, that while some of the cementing material may have been derived from the minerals in the sands, a considerable proportion of it must have been introduced from the muds, the finest clay fraction of which has been shown to be rich in a chlorite-like substance. Presumably as the muds became increasingly compacted, the water in them migrated into the more persistent pore spaces of the sands, and there deposited material carried in solution.

The abundance of springs and seepages in the South Gippsland Highlands and in the Otways district indicates that on exposure the arkose beds serve as channel-ways for underground waters. The felspars in such beds are little affected by the passage of the water. Two reasons can be advanced to explain this. Firstly, the abundant chlorite in the rock is more susceptible to attack than the felspar, so that the chemical activity of the water may be neutralized before it greatly affects the felspars. Secondly, the oxidation of the chlorite by the surface waters tends to convert it into limonite, which will form a protective coating about the felspar grains. There is no change in the MgO content of the rocks during this alteration of the chlorite to limonite, so that presumably the MgO, with the SiO_2 and Al_2O_3 of the chlorite, enters into clay minerals.

Even in the soils formed on the Jurassic rocks the felspars persist in abundance, and many of the grains are in a relatively fresh condition (Nicholls, 1936). It was thought that the felspars in the soils might be protected from weathering by a film of iron oxide, the residue of the original chloritic cement, but this is not so, and it seems likely, as Nicholls (1936) concluded, that either the potash and soda felspars are more stable than is generally believed, or more probably, that the Jurassic soils are so immature as to be little more than crumbled rock—crumbled through decay of the cement—and that soil erosion is so rapid as to remove the soil before the felspars can decompose *in situ*.

The Jurassic Terrane.

Any attempt to reconstruct the Jurassic terrane must take into account the prominent development of fresh-water felspathic sandstones, or arkoses, in the Upper Triassic of eastern Tasmania (Nye and Blake, 1938, pp. 45-49). These rocks closely resemble the Jurassic arkoses of Victoria, both in their mode of occurrence, association, and mineral composition. The similarity extends even to the presence in them of fragments of andesite-tuff such as characterize the Victorian rocks. It seems highly probable that both series of arkoses derived much of their material from the same general source, namely, a land-mass that is now sunk beneath Bass Strait. As the numerous granitic islands in the Strait indicate, this land-mass must have been largely composed of granitic rocks, with associated Palaeozoic and older sediments. There must also have been extensive areas of dacites and andesite-tuffs similar to those now outcropping in Victoria, and to a more limited extent in north-eastern Tasmania.

There has been some tendency to think that the two series of arkoses were formed simultaneously, despite the different character of their flora; but such an assumption is not justified, since both series of sediments were marginal to the same land area, and would reflect its composition equally, even though the basins in which they were deposited were formed at somewhat different times.

These basins apparently underwent slow, but continued, subsidence, because the sediments that filled them are of a shallow water character throughout. In Victoria, a subsidence of the order of 5,000 feet keeping pace with deposition is required. In Tasmania a similar, though earlier, subsidence of not less than 2,000 feet is required, since the total thickness of the arkoses and the associated Ross Sandstones and Upper Sandstones is of this order (Nye and Lewis, 1928; Nye and Blake, 1938).

The land occupying Bass Strait was probably mountainous. This is indicated by the mountainous nature of Wilson's Promontory, and the likelihood that many of the islands in the Strait are the tops of submerged mountains.

The limits of the Jurassic basin cannot be ascertained, but where its floor has been encountered around the margin of the present outcrops, it commonly slopes steeply, and appears to have considerable relief. At Griffith's Point, near San Remo, the Jurassic sediments are known to persist to more than 850 feet below sea-level, while a mile away the Cape Woolamai granite, which is apparently part of the same fault block (Edwards, 1942), rises to 300 feet above sea-level. This granite contributed much of the material in the Jurassic rocks now exposed at sea-level. Either the Eastern Passage separating the two formations marks the site of a pre-Tertiary Older Volcanic fault, or there is a fall of more than 1,150 feet in the floor of the Jurassic basin in a distance of 1 mile.

In the parish of Kongwak, an island of Silurian rocks outcrops at 420 feet above sea-level (Kitson, 1917), while a bore a mile to the north-west penetrated to about 600 feet below sea-level, without encountering the Silurian. Bores near Wonthaggi, and along the Powlett River, suggest that the Silurian outlier in Kongwak is part of a Silurian ridge trending south-westwards from this point. In these bores (Ann. Rept. Sec. Mines, 1917, Plate iv.), the Silurian occurs at depths ranging from 322 feet (Bore No. 681, Wonthaggi) to 1,311 feet (Bore No. 175, Wonthaggi), while other bores as deep as 2,633 feet (Bore No. 9, Powlett River) on either side of the ridge have failed to encounter the Silurian. The variable depths at which the Silurian occurs is due in part to faulting. Comparable inliers of Palaeozoic sediments occur at Turton's Creek (Ferguson, 1925) and at Boolarra (Ferguson, 1917) in South Gippsland.

South-west of Foster, the Palaeozoic sediments of the Hoddle Range rise to a height of 1,000 feet at Bald Hill, while their contact with the Jurassic rocks a mile to the north and north-west is at from 300 to 500 feet above sea-level. Near Lavers Hill the fall is 250 feet in a quarter of a mile.

On the northern margin of the Jurassic rocks in South Gippsland, the base of the Jurassic is about 450 feet above sea-level where it overlies the Silurian along Tyers River. A quarter of a mile to the north the Silurian rocks rise as high as 800 feet, and about 2 miles to the north they reach 1,000 feet above sea-level.

Along the Otway coast, at Apollo Bay, grits derived from a not far distant granite occur at sea-level, while bores at Wild Dog Creek, 2 miles away, penetrated more than 1,470 feet of

Jurassic sediments without encountering the underlying rocks. Faults may be present in the intervening country.

Elsewhere the floor of the basin may have sloped more gently. Thus, on Phillip Island, the Silurian lies beneath the Jurassic at a depth of 460 feet below sea-level at Rhyll, and of 306 feet at Cowes, 4 miles to the west, while on the other side of the island at Pyramid Rock, which is 5 miles south of Cowes, granite and Palaeozoic sediments rise about 50 feet above sea-level.

The Jurassic basin appears to have been a long narrow trough, not less than 350 miles, and probably more than 450 miles, long, with a width somewhat in excess of 50 miles. It had an uneven floor, which may have been as mountainous as its hinterlands. Deeper or quieter waters prevailed in the west where there is a greater development of mudstones, and along the central part of the basin. The floor of this basin subsided to a depth of about 5,000 feet, sufficiently slowly to maintain shallow water conditions throughout the whole period of deposition. In the early stages, a number of islands occurred in the lake or estuary, but as subsidence progressed these islands were buried by the accumulating sediments. The continued subsidence accounts for the steepness of shorelines like that between Griffith's Point and Cape Woolamai.

The waters of the basin were subject to strong and changing current action over most of its area—an unusual feature for a lake, though perhaps not for a shallow estuary. There seems, however, to be a complete absence of any gradation into marine beds, both in the Victorian Jurassic and in the Tasmanian Triassic. There is also a lack of current ripple-marks, though such ripple-marks were observed in the roof of the main roadway of the Shaft 18 area of the State Coal Mine.

Slow subsidence, and an adequate rainfall, combined to bring material to the basin in a fairly fine state of subdivision, chiefly as sands and muds. There is a surprising lack of marginal conglomerates, and of quartzose grits, but this may be due to inadequate exposure, and to erosion. In the Tasmanian Triassic a series of basal grits and conglomerates from 50 to 100 feet thick is recognized, but the only approach to this series in Victoria is the development of conglomerates between Tyer's River and Rintoul's Creek. The continued rejuvenation of streams feeding into the basin lead to rapid erosion of the hinterlands, and caused the felspars from the disintegrating igneous rocks to be carried into the waters of the basin before they had time to decompose greatly by weathering. Once in the lake they were rapidly sorted and dispersed by wave and current action, and were soon buried beneath later additions of sediment. From time to time, when subsidence temporarily failed to keep pace with sedimentation, they were subjected to local re-erosion and deposition by the lake waters.

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